Title	High Power CO_2 Laser Welding of Al_2O_3 Ceramics (Physics, Process, Instruments & Measurements)
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Citation	Transactions of JWRI. 1992, 21(2), p. 173-179
Version Type	VoR
URL	https://doi.org/10.18910/7669
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High Power CO_2 Laser Welding of Al_2O_3 Ceramics†

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and Yoshiaki ARATA****

Abstract

The welding characteristics of 87% Al_2O_3 were investigated using a high power CO_2 laser, and it was found that full penetration welding of 20 mm thick specimens is possible at a welding speed of 400 mm/min and a laser power of 10 kW. A sound bead was obtained with full penetration of specimens up to 10 mm at a suitable laser power and welding speed. The joint efficiency was about 60% for full penetration welding of a 4 mm thick specimen with the base material.

KEY WORDS :(High Power CO_2 Laser)(Laser Welding)(Alumina Ceramics)(Full Penetration Welding)
(Bending Strength)(Joint Efficiency)

1. Introduction

Recently, the technology of ceramics production has made tremendous advances and a variety of highly useful ceramics have been developed one after another. However, processing technologies have not kept pace with the development of new materials. In particular, joining techniques are lagging far behind and are restricting the utilization of materials in some instances. Various ceramic joining methods have been developed and researched, but a joining process that provides superior joining strength, heat-resistance and airtightness, and which can be applied to various ceramics has yet to be developed. One such possible joining method is fusion welding1),2), which would be an ideal method if ceramics could be fusion welded in the same way as metals. In this simple and easy method, the weld zone is continuous with the base material and joining can be carried out with much greater efficiency. In order to develop a joining technique for thick ceramics, the authors investigated the welding characteristics of 87% Al_2O_3 under various welding conditions using a high power CO_2 laser.

2. Experimental Procedure

As the heat source for welding, a 15 kw CO_2 laser (beam outer diameter 70 mm, module 1.5) was used with the Arata A-type laser focusing system, which employs an F10 focusing system with a spot diameter of approximately 0.8 mm. The focal position of the laser beam was set at 4 mm above the surface of the specimen ($a_b = 1.006$).

A plasma cutting nozzle was used to remove the plasma generated during welding, and a shielding nozzle was used to shield the laser beam from ceramic vapor and gas. A diagram of these nozzles is shown in **Fig.1.** Helium gas was used as both an assist gas and shielding gas.

When ceramics are welded without preheating, complex cracks are often formed. A welding furnace was thus constructed from firebricks with a gas burner inserted into the side. The specimens were preheated from the back and then furnace welding was conducted. The upper part of the furnace was open and the furnace was designed so as to allow the welding nozzles to travel inside the furnace. After welding the specimen was cooled inside the furnace.

The chemical composition and physical constants are shown in **Table 1.** The specimens were 20 or 40 mm wide × 80 mm long, with a thickness of 4-20 mm.

3. Results and Discussion

Figure 2 shows the bead cross sections under various welding speeds and laser powers. At a welding speed of

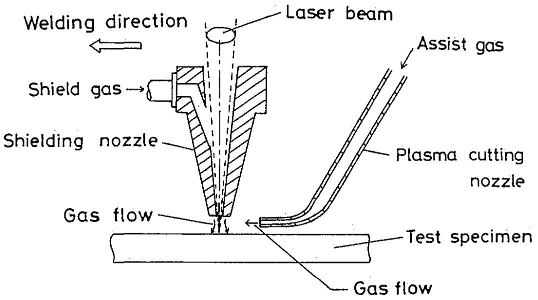

Fig.1 Schematic diagram of plasma cutting nozzle for welding.

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Transactions of JWRI is published by Welding Research Institute, Osaka University, Ibaraki, Osaka 567, Japan

Table 1 Chemical composition and physical constants of 87% Al_2O_3.

			$87\%Al_2O_3$
Chemical composition	Al_2O_3	%	87
	Others		SiO_2 10% MgO 2% CaO
Apparent density		g/cm^3	3. 4
Vickers hardness(500g)		—	1,300
Bending strength		kg/mm^2	30
Coefficient of thermal expansion (40~800℃)		1/℃ (×10^{-6})	7. 8
Heat conductivity(20℃)		$\frac{cal \cdot cm}{cm^2 \cdot sec \cdot ℃}$	0. 03
Specific heat		cal/g℃	0. 18

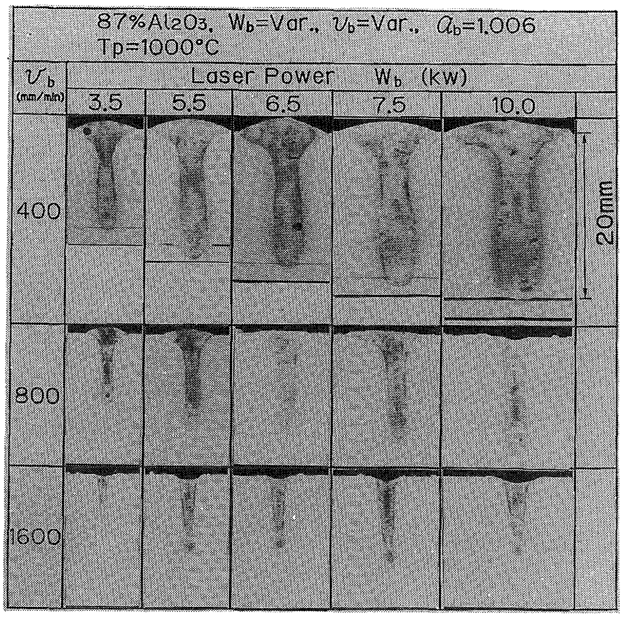


Fig.2 Bead cross sections of 87% Al_2O_3 weld bead at various laser powers and welding speeds.

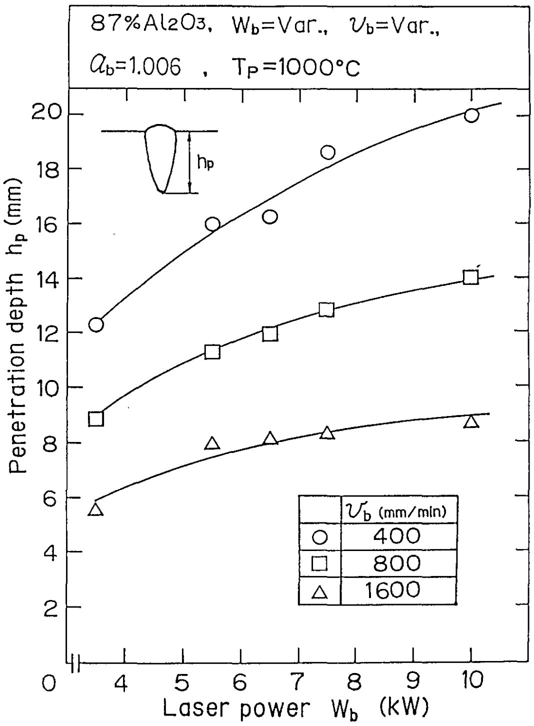


Fig.3 Relation between penetration depth and laser power at various welding speeds.

400 mm/min and a laser power of 3.5-10 kW, the bead is wine-cup shape with reinforcement of the weld surface and fairly large blowholes along the bond line. At a welding speed of 800 mm/min, there's no increase in reinforcement despite the increase in laser power, and at a laser power of 10 kW there is underfill of the bead surface. At a welding speed of 1600 mm/min the bead is wedge-shaped and all the bead surfaces show underfill with a great deal of spattering.

Figure 3 shows the relationship between the laser power and penetration depth at various welding speeds. At a welding speed of 400 mm/min and a laser power of 10 kW, the maximum penetration depth of 20 mm is obtained At each welding speed, as the laser powerincreases there's an increase in plasma generation. As plasma absorbs laser power, less laser heat energy reaches the wall of the beam hole, thus reducing the energy necessary for drilling. As a result, the penetration depth doesn't rise linearly with the laser power; instead, there is a tendency toward saturation.

During laser welding of 87% Al_2O_3, no surface cracks appear, but micro and macro cracks occur in the bead cross section. The cause of these cracks is thought to be the rapid input of laser power and low preheating temperature at the start of welding as well as the rapid rate of cooling after welding.

To try and prevent crack formation, the rise in heat input at the start of welding - what is called the "up slope time" - is controlled when welding ceramics. Welding with an up slope time of 1.5, 2.0, 2.5 and 3.0 seconds seems to reduce cracking, but it still occurs even with a long up slope time. Control of the up slope time therefore doesn't provide fundamental protection against cracks, and an up slope time of longer than 3.0 sec is not practical.

Secondly, at a preheating temperature of 800°, 1000° and 1200°C we examined whether or not cracks occurred in an 8 mm thick specimen with a laser power of 1-5 kW at a constant welding speed of 800 mm/min and an a_b value of 1.006. At each preheating temperature, the

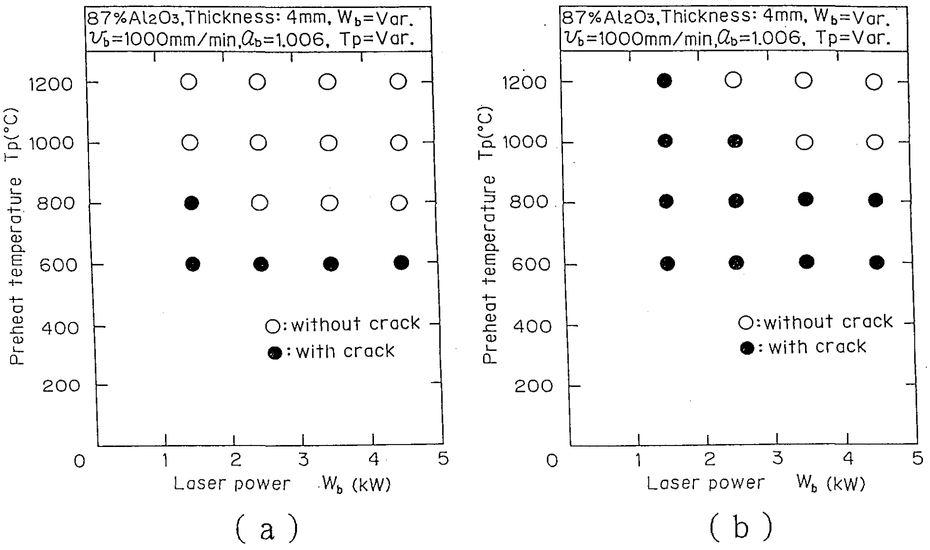


Fig.4 Relation between preheating temperature, laser power and cracking for at two types of cooling methods: (a) cooling method A (b) cooling method B

penetration depth increased as the laser power increased and, at a laser power of 3.0 kW and above, the beam fully penetrated the full 8 mm thickness. At each preheating temperature no cracks occurred in the welding zone and base material even with full penetration welding. When partial welding was carried out at a laser power of 3.0 kW or less, no cracks occurred at preheating temperatures of 1000° and 1200°C. However, as the preheating temperature approached 800°C, cracks began to appear.

Lastly, two types of cooling method were tried after welding. In the first method (cooling method A), the cooling rate was about 100°C/1hr until room temperature was reached. In the second method (cooling method B), the time until room temperature was reached was about 1 hour. The authors investigated whether or not cracks occurred in 4 mm thick specimens at a laser power of 1.5-4.5 kW with a constant welding speed of 1000 mm/min and an a_b value of 1.006. The results are shown in **Fig. 4.** At a preheating temperature of 600°C, cracks occurred using both cooling methods, the reason being the low preheating temperature. In the case of cooling method A, cracks also occurred at a preheating temperature of 800°C with a laser power of 1.5 kW. When the penetration depth was nearly the thickness of the specimen, cracks occurred from the back of the specimen and from the root of the bead. With this cooling method, however, cracks did not occur with any other welding conditions.

On the other hand, in the case of cooling method B, at a preheating temperature of 800°C or less cracks occurred on all specimens. It is thought that the cracks occurred because the contraction stress of the bead increases at the rapid cooling rate and that the base material around the bead is not able to relieve the higher contraction stress. At a preheating temperature of 1200°C with a laser power of 1.5 kW, cracks most likely occur because the penetration depth is only slightly shallower than the specimen thickness. Unlike full penetration, the base material around the bead is not able to relieve the contraction stress. Therefore, it is possible to reduce the occurrence of cracks by full penetration welding at a high preheating temperature and a high laser power. Also, as the specimen is subject to residual stress and tensile stress during solidification after welding, to prevent cracks it is necessary to relieve these stresses by slow cooling. In other words, a slow cooling rate is better for relieving stress.

As mentioned above, to prevent cracks a long cooling time is necessary after welding with a high preheating temperature. It was also found that full penetration welding reduced the likelihood of cracks compared to partial penetration welding. **Figure 5** shows the bead cross sections using 6 and 8 mm thick specimens at a preheating temperature of 800°C with a constant welding speed of 800 mm/min, an a_b value of 1.006 and a laser power of 2.5 kW. It was found that there is a difference in the occurrence of cracks due to the difference in thickness under the same welding conditions; this is related to the difference found earlier between full and partial penetration welding. With partial penetration welding, two kinds of cracks were recognized: cracks parallel to the bonding line, which are thought to be caused by contraction stress during solidification, and cracks caused from the back of the section of base material under the

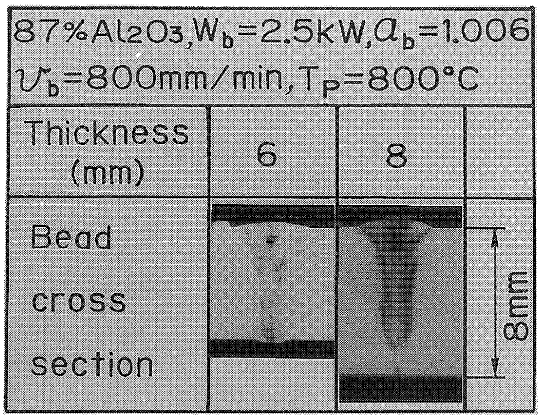
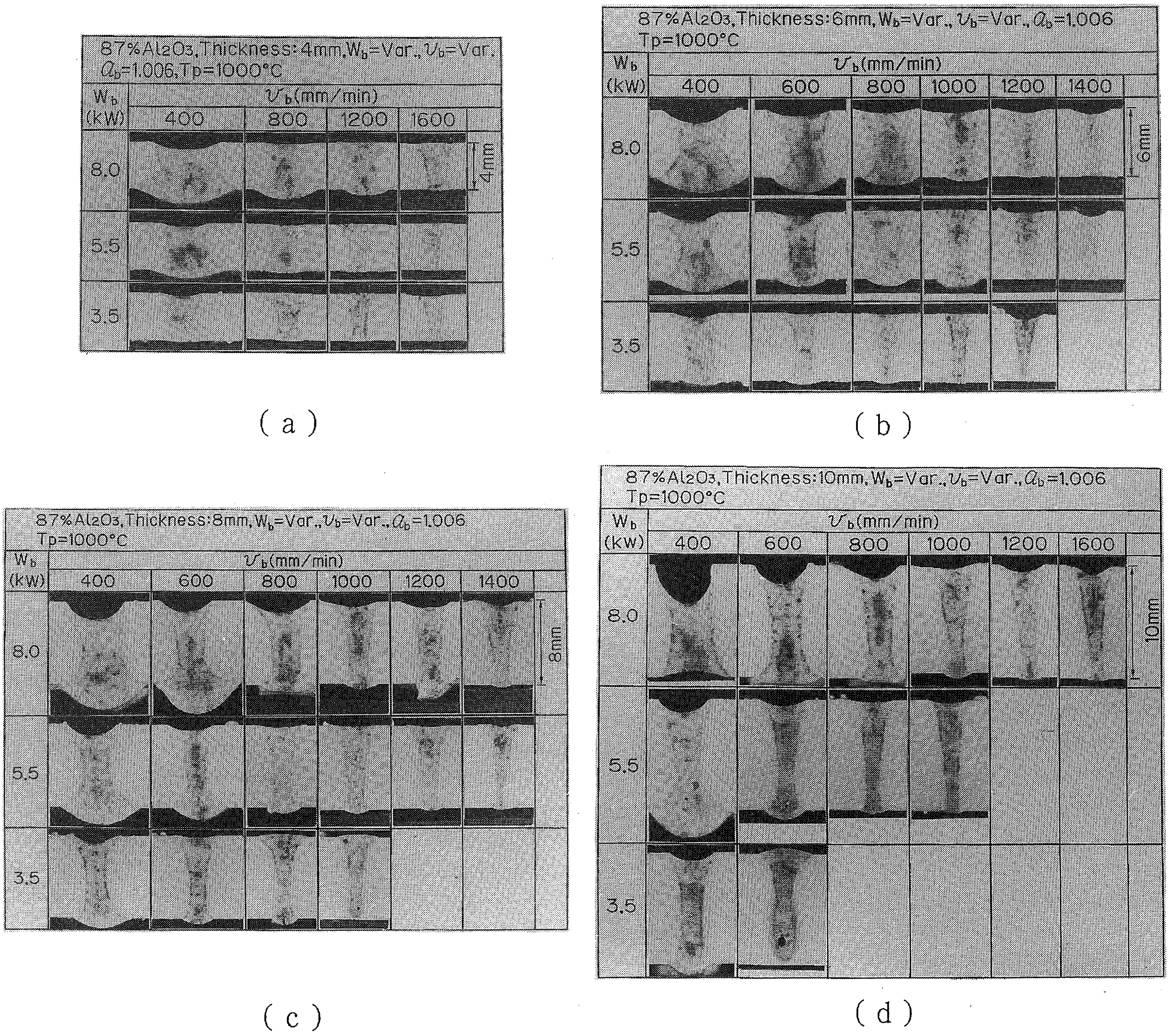


Fig.5 Cross sections of weld bead for specimen thickness of 6 and 8 mm.

bead. This latter type is thought to be due to the difference in the distribution of contraction stress between full and partial penetration welding. With partial penetration welding, tensile stress is caused between the shrunk root and the unmelted part, which restrains contraction stress under the bead. Cracks occur when the tensile stress exceeds the plastic deformation limit of the base material. With full penetration welding cracks don't occur even if tensile stress is present, as there is no unmelted part which restrains shrinkage stress under the bead.

Figure 6 shows the bead cross sections of full penetration welding using specimens thicknesses of 4, 6, 8 and 10 mm at various welding speeds and laser powers. With full penetration, as the thickness increases there's an

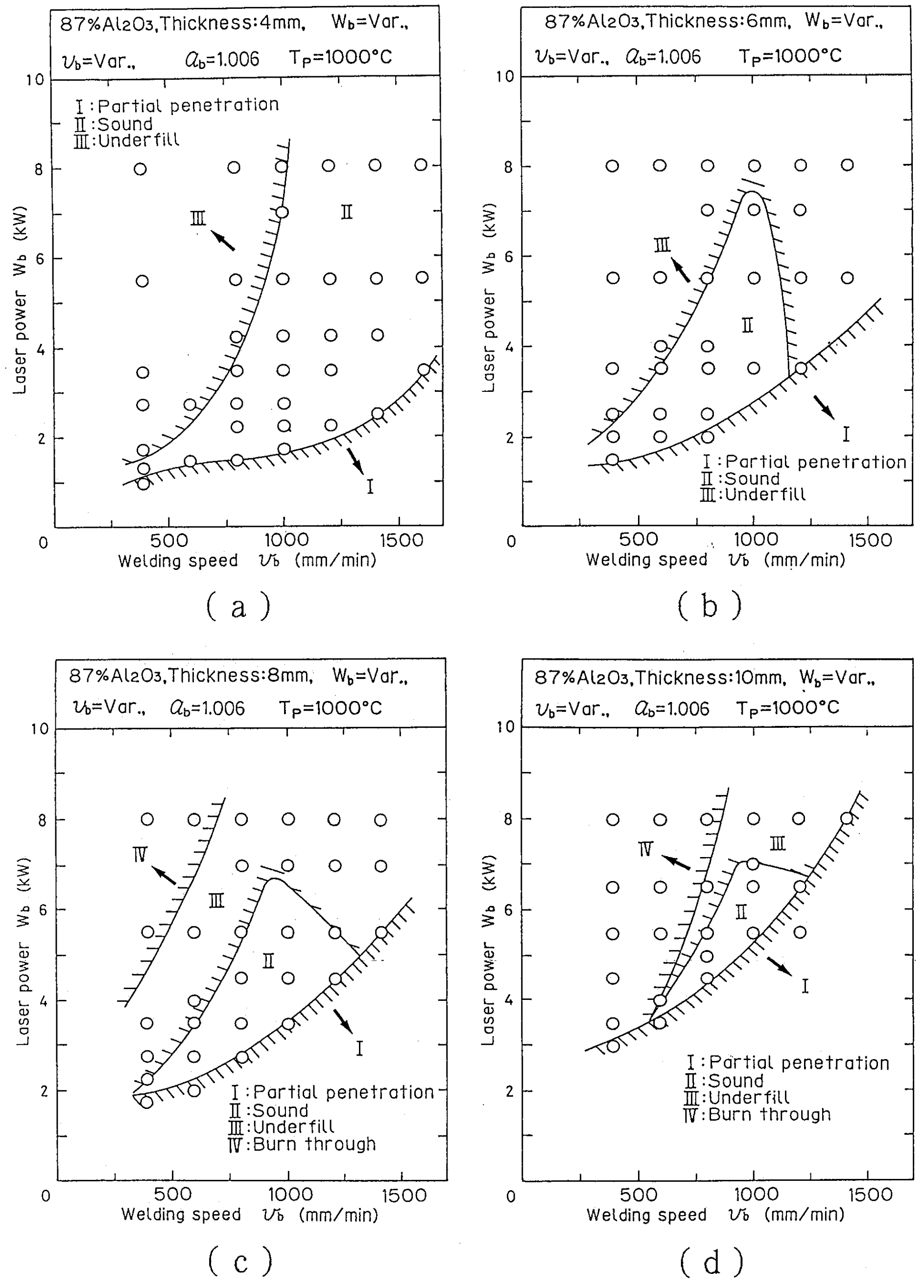


(a) (b)

(c) (d)

Fig.6 Bead cross sections of weld bead at various laser powers and welding speeds: (a) 4 mm thick (b) 6 mm thick (c) 8 mm thick (d) 10 mm thick increasing tendency to have difficulty forming the weld reinforcement and to underfill the bead surface when the welding speed is slow. At a laser power of 8.0 kW, there is underfill of the bead surface regardless of the welding speed with specimen thicknesses of 6 mm or more. Also, burn-through from the backside of the specimen was found to occur at a welding speed of 400 mm/min for specimen thicknesses of 8 mm or more.

Figure 7 shows the the bead shape zone obtained at different laser powers and welding speeds for each thickness. There are three different possible zones 4 and 6 mm thick and into four different zones at 8 and 10 mm. The zones are: partial penetration (1), a sound bead shape with full penetration (2), an underfill bead surface (3), and burn-through (4). At 4 mm thick the underfill zone is at a high laser power and a low welding speed, and the sound bead shape zone is wide. But at 6 mm thick and above underfill is insufficient at a high laser power and high welding speed, and the sound bead shape zone shows a tendency to be small as the thickness



(a) (b) (c) (d)

Fig.7 Bead shape zones correlated with welding speed and laser power various thickness: (a) 4 mm thick (b) 6 mm thick (c) 8 mm thick (d) 10 mm thick increases. Also, at 8 mm thick and above there is burn-through, i.e. the molten pool can not be maintained because the melted material drops out from the back.

The strength of the welding joint was evaluated using the JIS four-point bend test[3]. As shown in **Fig.** 8, a 40 mm wide area in the center of a 4 mm thick specimen was welded by full penetration welding. Bending test pieces measuring 4 mm wide × 40 mm long were then cut out using a diamond cutter so as not to include the beginning of the weld and end crater. The upper and lower sides of the cut test pieces (the bead surface and back) were polished flat using emery paper and the edges were rounded. The test pieces produced in this way were then tested using an Instron universal testing instrument. Ten or more tests were conducted for each set of welding conditions and the data was then statistically treated using a Weibull plot to evaluate the reliability of the data. The base material was similarly tested for comparison purposes. The bending test of ceramics has been established as the test method for strength of material. There is no better method for strength of the weld.

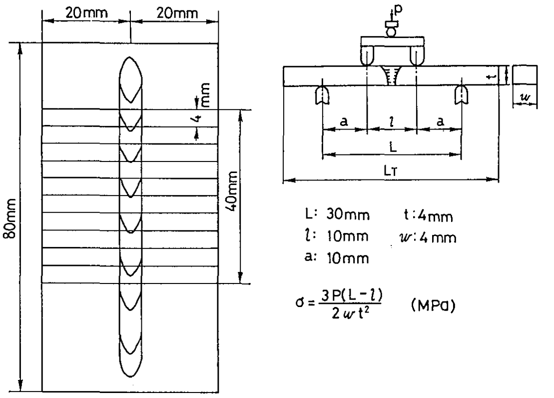


Fig.8 Sectioning of specimen for a four-point bending test.

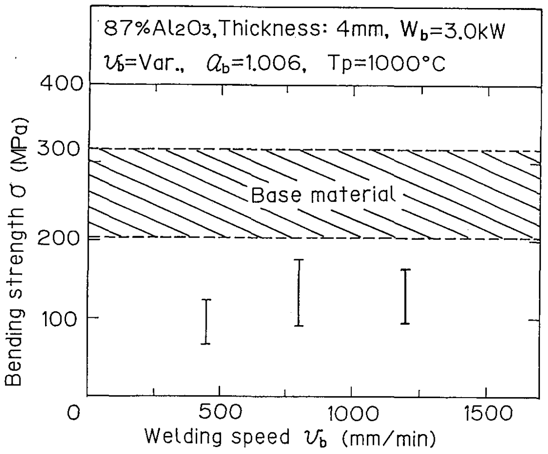


Fig.9 Relation between bending strength and welding speed.

Full penetration welding of the 4 mm thick specimens was carried out at a welding speed of 400, 800 and 1200 mm/min with a constant laser power of 3.0 kW, a preheating temperature of 1000°C and an a_b value of 1.006. After welding the test pieces were cut, polished and rounded as explained above and bending tests were performed. **Figure 9** shows the relationship between the welding speed and bending strength. The maximum bending strength was about 180 MPa at a welding speed of 800 mm/min, and the joint efficiency with a base material of about 300 MPa was approximately 60%. At a welding speed of 400 and 1200 mm/min the pieces fractured in the center of the weld bead, but at a welding speed of 800 mm/min the fracture path was from the bond to the base material. The Weibull plot at a welding speed of 800 mm/min is shown in **Fig.10** with the base material. The Weibull coefficient (m value) showed the reliability of the bending strength of the weld to be about the same as that of the base material; although it is a little lower, the data scattering is nearly the same as the base material.

4. Conclusion

This study was designed to establish a method of joining thick ceramics. For this purpose the welding characteristics of 87% Al_2O_3 were investigated using a

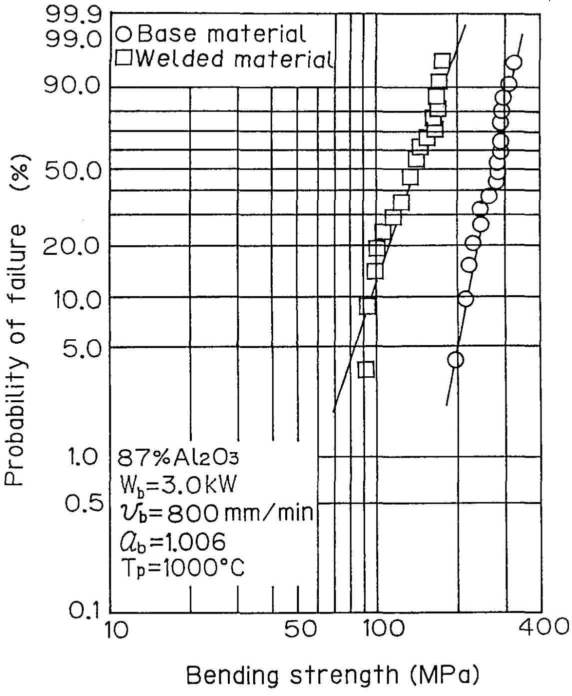


Fig.10 Example of Weibull plot of bending strength.

high power CO_2 laser.

The results can be summarized as follows:

(1) It was found that full penetration welding of 20 mm thick specimens is possible at a welding speed of 400 mm/min and a laser power of 10 kW.

(2) It was found that a sound bead shape was obtained with full penetration welding of specimens up to 10 mm thick at certain laser powers and welding speeds.

(3) The joint efficiency of full penetration welding for a 4 mm thick specimen with the base material was about 60%.

References

1) M.Tomie, N.Abe, T.Oda, S.Noguchi, Y.Arata: Trans. of JWRI,**18**-1(1989),37-41
2) M.Tomie, N.Abe, T.Oda, S.Noguchi, Y.Arata: J. High Temp. Soc. Jpn.,**16**-2(1990),99-104 (in Japanese)
3) JIS R 1901 (1981), "Testing method for flexural strength (modulus of rupture) of high performance ceramics"